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**ON THE USE OF RELATIVE VELOCITY EXPONENTS
FOR JET ENGINE EXHAUST NOISE**

by James R. Stone
Lewis Research Center
Cleveland, Ohio 44135

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by James R. Stone

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

ABSTRACT

The effect of flight on jet engine exhaust noise has often been presented in terms of a relative velocity exponent, n , as a function of radiation angle. Prediction methods (e.g., Bushell (1975)) have also been proposed on this basis. The value of n is given by the OASPL reduction due to relative velocity divided by 10 times the logarithm of the ratio of relative jet velocity to absolute jet velocity. In such terms, classical subsonic jet noise theory (Ffowcs Williams (1963)) would result in a value of $n \cong 7$ at 90° to the jet axis with n decreasing, but remaining positive, as the inlet axis is approached and increasing as the jet axis is approached. However, flight tests have shown a wide range of results, including negative values of n in some cases. It is shown in this paper that the exponent n is positive for pure subsonic jet mixing noise and varies, in a systematic manner, as a function of flight conditions and jet velocity. On the basis of calculations from simple empirical models for jet mixing noise, shock noise and internally-generated noise, it is shown that when other sources are present, the resulting range of n is increased over the range for jet mixing noise, and in some cases negative values of n are obtained.

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INTRODUCTION

To assess the impact of jet noise on the environment of the airport vicinity it is necessary to predict the effect of flight on jet engine exhaust noise. For new or proposed aircraft particularly, such predictions will be based at least in part on model and full-scale static and simulated flight experiments. Because of costs, to rely solely on full-scale flight tests would severely limit the number of configurations and concepts that could be tested. Therefore, it is of great importance to be able to predict in-flight noise from static or simulated-flight data.

In many recently reported studies on the effect of flight on jet engine and model jet exhaust noise, the results have been presented in terms of a relative velocity exponent, n , defined as follows:

$$n \equiv [\text{OASPL}_F - \text{OASPL}_S + 10 \log (1 - M_o \cos \theta)] / \left[10 \log \left(\frac{V_j - V_o}{V_j} \right) \right]$$

The flight geometry is illustrated, and some of the key parameters are defined, in figure 1. (All symbols are defined in appendix A.) Such data are typically presented as plots of n versus θ , the angle from the inlet axis. Also, prediction methods for jet noise flight effects (e.g., Bushell (ref. 1)) have been proposed on the basis that n can be defined as a unique function of θ . However, it should be pointed out that n is not a physical quantity, but an expression based on assumed relationships. It will be pointed out that such relationships do not accurately and uniquely represent the physical processes. Furthermore, it will be shown that the exponent n is sufficiently sensitive to the measured OASPL's that the presence of even small amounts of non-jet mixing noise can result in negative values of n . Such results could easily be mistakenly interpreted as an increase in jet-mixing noise in flight. It will be argued, therefore, that prediction methods should not be formulated on the basis of n as a function of θ .

As an indication of this problem, classical subsonic jet noise theory (Ffowcs Williams (ref. 2)) would predict a value of $n \cong 7$ at $\theta = 90^\circ$

with n decreasing, but remaining positive, as θ approaches 0° and increasing as θ approaches 180° ; however, n would not be a unique function of θ . A composite plot of typical experimental values of n available from the literature as a function of θ is shown in figure 2; the proposed prediction curves of Bushell (ref. 1) and Hoch (as given in ref. 3) are also shown. The flight data (refs. 1 and 3 to 7) show a wide range of results, including negative values of n in some cases. (Positive values of n indicate noise reduction in flight, while negative n values indicate noise amplification in flight.) The prediction of Bushell (ref. 1) also indicates an angular range of negative n values, primarily in the forward quadrant, consistent with some of the engine data (refs. 1 and 3). On the other hand the simulated-flight data exhibit positive n values at all angles for shock-free jets (e.g., refs. 8 and 9, which are typical of such data), with the exception of some of the data of reference 4. These latter data (ref. 4) have a correction applied for an assumed sound absorption by the free jet turbulent shear layer, without which the n values would be higher and closer to the other model data. The prediction curve proposed by Hoch (as given in ref. 3) appears to represent a compromise between engine and model jet data.

It will be shown in this paper that the exponent n for pure jet mixing noise varies systematically as a function of jet conditions and flight velocity and has a positive value. It will also be shown that when the effects of shock noise and/or internally-generated noise are considered, the range of n values calculated is even greater, and in some cases negative values of n are calculated. These calculations will be based on the empirical methods of reference 10 for jet mixing noise, shock noise and internally-generated noise. Furthermore, it will be shown that these results are at least qualitatively consistent with recent fundamental experimental and analytical studies.

JET MIXING NOISE

Forward velocity exponents for jet mixing noise herein are computed from the relations of reference 10. The calculated values of n

are compared with those obtained from model jet simulated flight tests (free jet, ref. 8) in figure 3. Data for various V_j/c_a at constant jet temperature are shown in figure 3(a), and data for various jet temperatures (and consequently various ρ_j/ρ_a) with constant jet velocity are shown in figure 3(b). The values of n near $\theta = 90^\circ$ are in good agreement with those calculated from the jet mixing noise prediction as are the trends of n with jet velocity and jet density. At large angles the absolute agreement is not as good, but these discrepancies do not seem large when compared with the wide range of n shown in figure 2. At least part of the discrepancies may be due to the method used in transforming the free jet data to flight (ref. 8), particularly the correction for propagation through the free jet shear layer and the absence of any correction for the distributed nature of the jet noise source. Similar exponents result for calculations based on the Ffowcs Williams model (ref. 2), as described in appendix B.

TOTAL JET ENGINE EXHAUST NOISE

For sources other than jet-mixing noise, the values of n vary considerably with jet velocity and to some extent with flight Mach number, M_o . When additional sources are present, such as internally-generated noise and/or shock noise, the values of n calculated would be intermediate between those calculated for jet mixing noise, n_j , and those calculated for the other sources, moving with the airplane, n_o . For fixed jet conditions and M_o , the value of n obtained potentially will be influenced by the sources other than jet mixing noise. These effects are illustrated for a subsonic jet case in figure 4(a) for a supersonic jet in figure 4(b). The total noise exponent, n , as calculated by the methods of reference 10, is plotted against θ for various levels of nonjet noise relative to total noise under static conditions, $OASPL_S - OASPL_{o,S}$ (difference in level, ΔdB). Also indicated by the cross-hatched bands are typical ranges of nonjet-mixing noise for jet engines (ref. 11). It can be seen that the numerical value of n is quite sensitive to OASPL increments. It can further be seen that even for nonjet-

mixing noises significantly less than total noise statically, the exponent n differs significantly from that predicted for pure jet mixing noise, n_J . It is clear that even when the nonjet-mixing noise is less than the jet-mixing noise statically (e.g., $OASPL_S - OASPL_{O,S} = 3$), the relative velocity exponent n becomes negative. These predicted results are consistent with a recent experimental study (ref. 12) wherein various known levels of internal noise were introduced into a model jet operating in a free jet flight simulation facility. Thus, it can be seen that the negative values of n obtained in some flight tests (e.g., refs. 1 and 3) can be related primarily to nonjet-mixing sources. It is of particular interest to note that the sensitivity of n to nonjet-mixing noises, for fixed $OASPL_S - OASPL_{O,S}$, increases with increasing V_j/c_a . Thus although the level of internal noise relative to total noise may decrease with increasing jet velocity, the effect of internal noise on n may not be diminished at all with increased jet velocity. It is conceivable (from the arithmetic involved) that under some conditions the effect of internal noise on n may increase with increasing velocity even though the level of internal noise relative to total noise decreases.

COMPARISON WITH FLIGHT DATA

This section presents comparisons of predicted relative velocity exponents with experimental data from aircraft flyover and aerotrain tests (refs. 4, 6 and 7).

Turbofans

Experimental and predicted relative velocity exponents for turbofan engines are shown in figure 5. The contribution of turbomachinery noise was subtracted from the experimental data. Figure 5(a) contains comparisons for refanned JT8D engines in a DC-9 airplane (ref. 7), while figure 5(b) contains similar comparisons for conventional JT8D engines in a B-727 airplane (ref. 6). In general the agreement between experimental and calculated exponents is acceptable. What appears to be a

large error in exponent actually corresponds to about ± 3.5 dB in OASPL. (A 1.0 dB change in Δ OASPL produces a 0.9 to 1.6 change in n for these conditions.) The experimental data trends are in general agreement with calculation, although consistently high values of n are calculated for the B-727 conditions (fig. 5(b)), which corresponds to as much as ~ 2 dB in the forward quadrant.

Turbojet

Experimental and predicted relative velocity exponents for a J85 turbojet engine installed on the Bertin aerotrain (ref. 4) are shown in figure 6. Comparisons for simulated-flight Mach numbers of 0.12 and 0.24 are shown in figures 6(a) and 6(b), respectively. At the highest jet velocity, shock noise is calculated to have a significant effect which is absent at the two lower jet velocities. (The observed excess static noise above that predicted for jet-mixing and internally-generated noises was projected to flight assuming it to be a shock-associated noise, as in ref. 10.) Except for radiation angles of 140° or greater in rear quadrant, the agreement is even better here than for the turbofan engines (fig. 5). Further study is required to determine to what extent this large-angle problem is due to shortcomings of the prediction methods and how much error may be due to experimental inaccuracies.

CONCLUDING REMARKS

It has been shown in this paper that the relative velocity exponent n varies predictably as a function of jet conditions and flight velocity even for pure jet mixing noise. It has been further shown that when the effects of shock noise and internally-generated noise are considered, the range of n values predicted is even greater. These findings have been shown to agree reasonably well with experimental data and, at least qualitatively, with fundamental studies. Experimental plots of n versus angle exhibit considerable scatter, and the numerical value of n is quite sensitive to the OASPL measurement. Based on these findings,

the correlations and predictions of flight effects on the basis of relative velocity exponents as a function of angle are considered inadequate and misleading.

APPENDIX A

SYMBOLS

c_a	ambient sonic velocity
n	relative velocity exponent (eq. (1)), dimensionless
M	Mach number, V/c_a , dimensionless
OASPL	overall sound pressure level, dB re $20 \mu\text{N/m}^2$
V	velocity
ρ	density
θ	angle referred to jet inlet axis

Subscripts:

a	ambient
c	convection
F	flight
J	jet mixing
j	fully-expanded isentropic jet (primary stream)
S	static
o	aircraft, or moving with aircraft

APPENDIX B

COMPARISON OF EMPIRICAL AND THEORETICAL COMPUTATIONS

In order to establish that the results presented in this study are not unique to the jet-mixing noise prediction method (ref. 10), comparisons are made in this section between empirical and theoretical computations. Typical plots of n versus θ for jet-mixing noise are shown in figure 7 for a range of conditions. The values are computed from the empirical model of reference 10 and the theoretical model of Ffowes Williams (ref. 2) using turbulence parameters from both references 13 and 14.

Effect of Flight Mach Number

The effect of flight Mach number, M_0 , is illustrated in figure 7(a) for a typical subsonic case, $V_j/c_a = 1.0$ and $\rho_j/\rho_a = 0.30$. Although the absolute values calculated by the various methods differ somewhat, the trends with θ and M_0 are very similar, and M_0 has very little effect on n for these subsonic conditions. None of these models indicates negative n values for subsonic jets.

Effect of Jet Velocity

The effect of jet velocity is shown in figure 7(b) for $M_0 = 0.2$ and $\rho_j/\rho_a = 0.30$. The absolute values of n as well as the effect of V_j/c_a on n are predicted differently by the several models. Regardless of which model is used, however, it can be seen that n is not a unique function of θ . The decrease of n with increasing θ in the "zone of silence" near the jet axis for the theoretical models is due to a difference in accounting for supersonic convection effects. Although it is beyond the scope of this study to determine the validity of this decrease, there is some experimental evidence (e.g., ref. 4) that such effects may

occur for supersonic jets, even to the extent of producing negative n values in the "zone of silence," as predicted from references 2 and 13.

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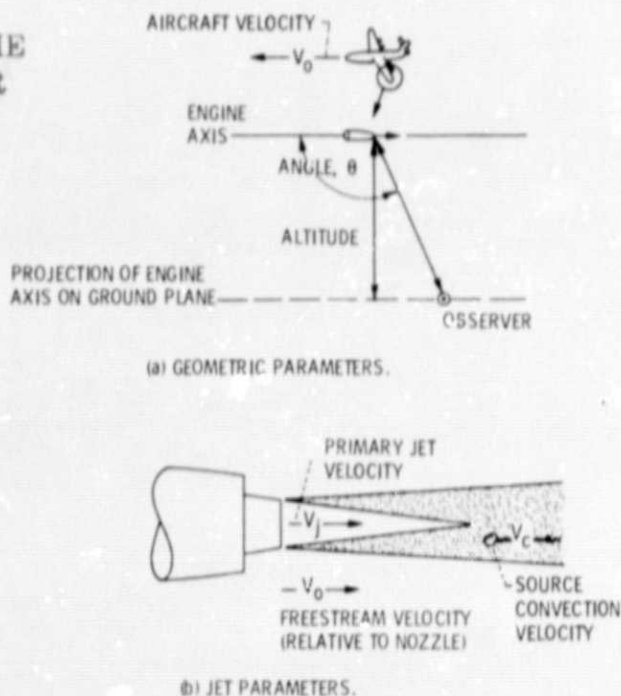


Figure 1. - Flight effects on exhaust noise - terminology for level flight at aircraft Mach number M_0 .

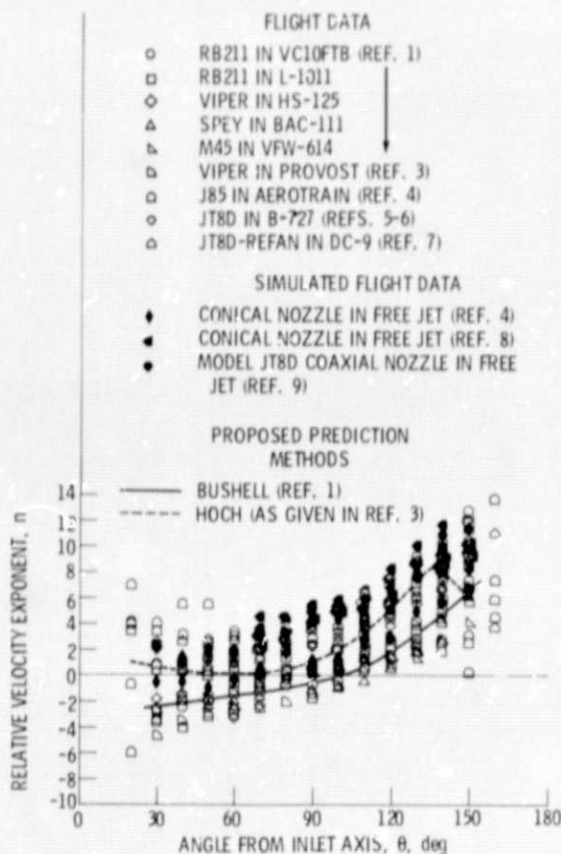


Figure 2. - Typical experimental relative velocity exponents and proposed predictions.

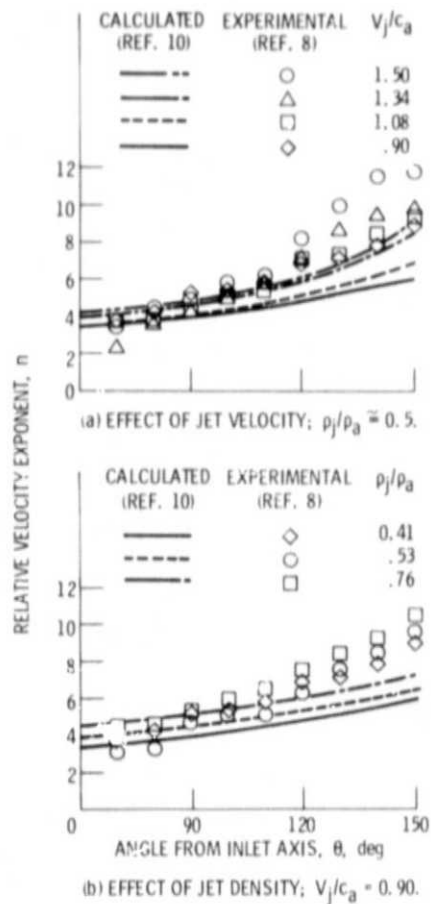


Figure 3. - Comparison of experimental and calculated relative velocity exponents as function of angle for model jet in free-jet flight simulation facility.

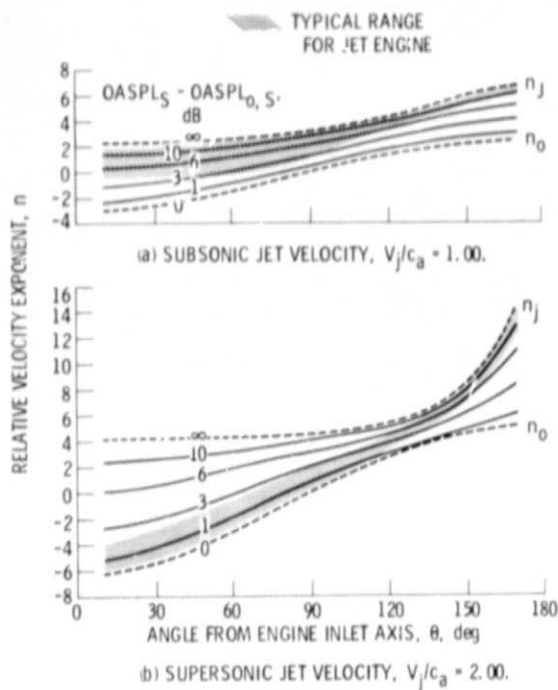


Figure 4. - Effect of non-jet-mixing noise on relative velocity exponents; $M_0 = 0.20$.

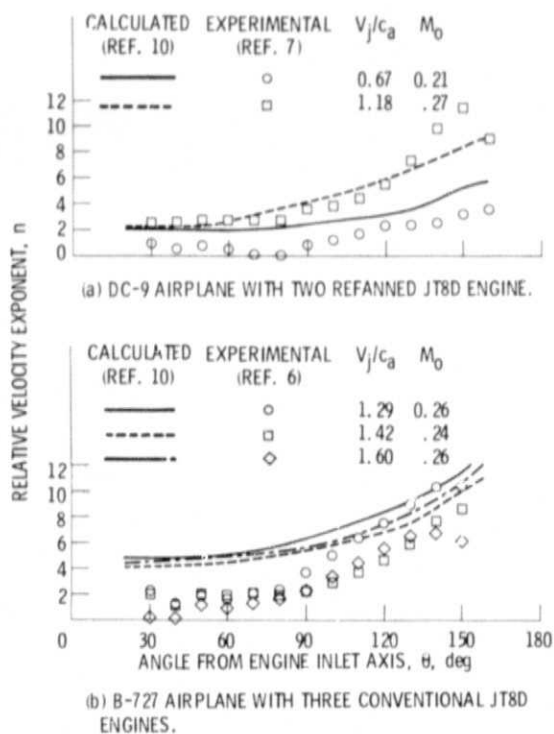


Figure 5. - Comparison of experimental and calculated relative velocity exponents as a function of angle for turbofan engines.

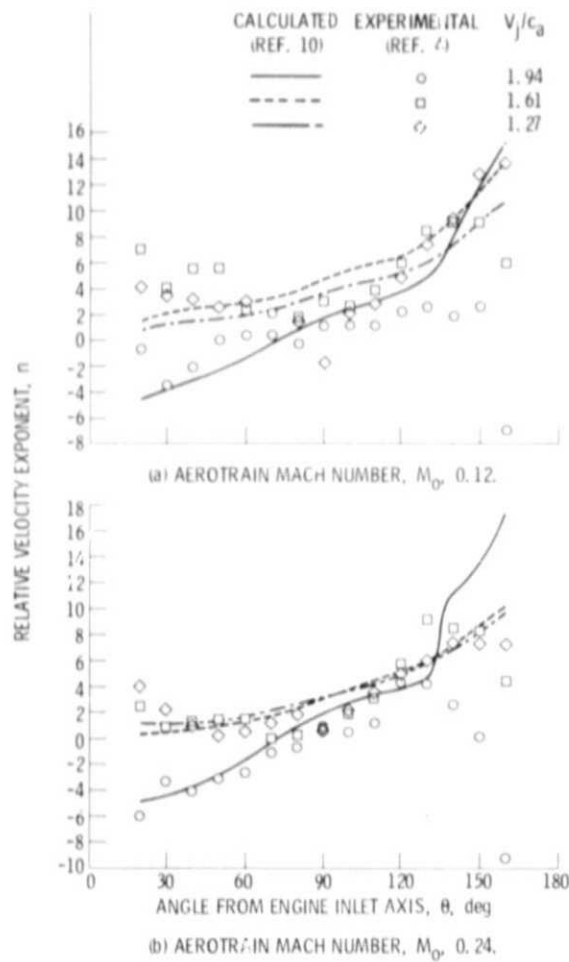
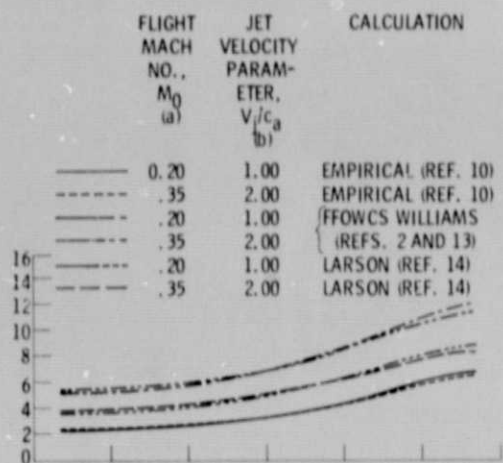
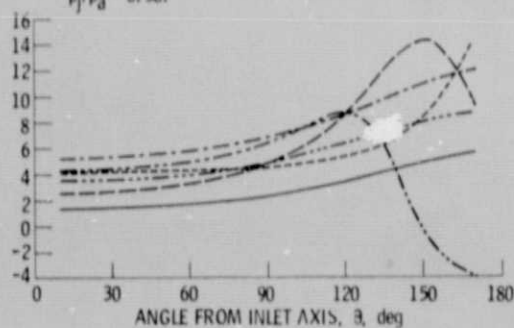


Figure 6. - Comparison of experimental and calculated relative velocity exponents as function of angle for J85 turbojet engine on Bertin Aerotrain.



(a) EFFECT OF FLIGHT MACH NUMBER; $V_j/c_a = 1.00$,
 $\rho_j/\rho_a = 0.30$.



(b) EFFECT OF JET VELOCITY; $M_0 = 0.20$, $\rho_j/\rho_a = 0.30$.

Figure 7. - Typical plots of relative velocity exponents
against angle for jet mixing noise.